Calibration of a passive rem counter with monoenergetic neutrons

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1. Introduction

Rem-Counters are the most used instruments for neutron survey for radiation protection purpose. Most of them are active instruments using a proportional counter as thermal neutron detectors but passive versions are also used Passive Rem-Counters are used mainly with activation foils (gold or dysprosium) or with TLD detectors. In the latter case, the common choice is to use one TLD enriched in ^{7}Li to detect the photon component usually associated to the neutron field and a TLD enriched in ^{6}Li to detect both the neutron and the photon component of the radiation field. The subtraction of the two signals is used to evaluate the neutron component. Of course, the detection limit and the uncertainty of this technique is a function of the intensity of the photon field that represents a noise signal. Passive track detectors coupled to a ^{10}B converter are also used (Burgkhardt et al., 1986, 2002; Agosteo et al., 2009).

Recently a dual detector extended range Rem-Counter (Agosteo et al., 2010), both active and passive was proposed. The moderator can host both a passive and an active detector, but not simultaneously. The purpose of the passive detector is for environmental monitoring. For example, it is useful in situations where the photon component associated to the neutron field is important or when the neutron field is pulsed and the active rem counters can fail. Moreover, this technique can be used where it is necessary to build large neutron measuring nets (with many tens of measuring points), for which active instrumentation may be unacceptable for its costs.

The passive version of the recently proposed Rem-Counter, which is the focus of this work, is based on a thermal neutron detector composed of two CR-39 nuclear track detectors coupled to an enriched ^{10}B converter. It has the advantage of being insensitive

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to the photon component of the radiation field and exhibits a very low detection limit, at least when compared to other passive techniques. It has been characterized in terms of intercomparison with other instruments in workplaces neutron fields (Agosteo et al., 2009; Silari et al., 2009).

One of the main issues in using CR-39 detector coupled with a ^{10}B converter is to define an etching procedure of the detectors capable of preserving the information. In fact, alpha particles (94% having $E = 1.47$ MeV and 6% having $E = 1.78$ MeV) and ^{7}Li nuclei (94% having $E = 0.84$ MeV and 6% having $E = 1.0$ MeV) obtained via interaction of thermal neutron with ^{10}B have a range of 6.3 μm and 3.6 μm in CR-39 respectively (considering the most probable energies). Consequently an aggressive etching can erase the tracks. Moreover it is important to define filters on the track parameters in order to separate the signal (i.e. number of tracks generated by the (n,alpha) reaction on ^{10}B) from noise. The aim of this paper is to describe the track analysis technique used for noise reduction and the metrological confirmation of the response function used in the former works cited above, against reference irradiation with monoenergetic neutron beams at PTB.

2. Material and methods

The passive Rem-Counter hosts as inner detector two CR-39 PADC track detectors coupled with an 90% enriched ^{10}B converter (Fig. 1 right). The track detectors are supplied by Intercast (Parma—Italy) and the Enriched Converter Screen BE10 by Dosirad (France). Tracks on the detectors are produced by alpha particles and ^{7}Li nuclei obtained via interaction of thermal neutron with ^{10}B. The detectors were etched in a 6.25 mol aqueous NaOH solution at 98 °C for 40 min. Under these etching conditions the bulk attack velocity, measured with the fission fragments technique, is $V_B = 10 \pm 0.2$ μm/h (Caresana et al., 2012). The removed layer is 6.7 μm thick which is a good compromise between the dimension of the etched tracks and detection efficiency (Caresana, 2007).

The detectors are analysed with a commercial reader called Politrack, developed at the Politecnico di Milano and marketed by MIAM srl (Italy). More details about the track reading are given in the results and discussion paragraph.

The Rem-Counter (Fig. 1 left) consists of a polyethylene sphere 25 cm in diameter with a lead shell inside to extend the response function to high energy neutrons and cadmium insets to tune the response function to be as close as possible to the fluence to $H^*(10)$ conversion coefficients. An external plug is used to place the detector at the centre of the sphere.

The irradiation to monoenergetic neutron beams were performed at PTB (Germany) with the following energies: 0.565 MeV, 8.08 MeV, 14.8 MeV and 19 MeV.

3. Results and discussion

A particular care was devoted to the analysis of the track detectors in order to work out an effective procedure of noise reduction. The signal due to charged particles coming from thermal neutrons interaction on ^{10}B must be separated from two main sources of noise. The first is mainly due to surface defects on the detector; the second is produced by a direct interaction of fast neutrons (not thermalized by the moderator) with the CR-39. In this case the tracks generation is due to recoil protons. This is an unwanted contribution to the signal because the interest lies only in the thermal neutron reactions on ^{10}B. One way to separate tracks due to recoil protons and heavier charged particles is to set a threshold in terms of LET. In fact protons cannot have an LET in CR-39 higher than about 100 keV/μm (proton edge), while alpha and ^{7}Li particles have an LET much higher than 100 keV/μm at the energies of interest. The Politrack can perform a measurement of the mean LET (Caresana et al., 2012). In particular, through the measurement of the major and minor axis of the tracks, it is possible to evaluate the ratio V between the track attack velocity and the bulk attack velocity. The mean value of V is a function of the mean LET of the particle, that is the deposited energy divided by the particle path length.

It is possible to calculate the mean LET using the SRIM code, (Ziegler, 2012) simply dividing the initial particle energy by the particle range. Table 1 reports this calculation for the energies of interest. The energy distribution of the secondary particles coming from the boron converted is almost uniformly distributed in energy because of the self-adsorption. Nevertheless it can be noted that the mean LET is rather constant, also for particles of low energy particles that are probably not detected, and a peak in terms of mean LET is expected.

In Fig. 2 are reported the distributions of V, tracks area and mean LET for three detectors. The detector n°1808 (upper graphs) is irradiated with 0.565 MeV neutron energy, the detector n° 1792 is irradiated with 19 MeV neutron energy while the detector n°1753 is an example of background detector. Several considerations can be drawn from these graphs:

1) as expected form the SRIM calculation the mean LET distributions have a peak at about 190 keV/μm that is due to the alpha particles and a peak around 300 keV/μm that is due to ^{7}Li particles. While the alpha peak is in agreement with the calculated mean LET (Table 1) the ^{7}Li one overestimates the calculation. This is an effect of the over-etching that over-enlarges the tracks mimicking an higher mean LET.
2) The mean LET distribution of the 1808 detector (0.565 MeV irradiated) has a continuum down to tens of keV/μm, while the detector 1792 (19 MeV) has a peak around 80–90 keV/μm. This

Fig. 1. Picture of the Rem-Counter (left) and sketch of the assembly of the passive thermal neutron detector (right).

Table 1
Mean LET of alpha and ^{7}Li particles calculated with SRIM.

Alpha		Mean LET	Lithium		Mean LET
Energy/keV	Range/μm	keV/μm	Energy/keV	Range/μm	keV/μm
325	1.89	172	350	1.93	181
350	1.99	176	375	2.01	187
375	2.08	180	400	2.09	191
400	2.17	184	450	2.24	201
450	2.35	191	500	2.38	210
500	2.53	198	550	2.52	218
550	2.7	204	600	2.65	226
600	2.88	208	650	2.77	235
650	3.05	213	700	2.89	242
700	3.22	217	800	3.13	256
800	3.57	224	900	3.35	269
900	3.93	229	1000	3.57	280
1000	4.3	233	Average		225
1100	4.67	236			
1200	5.06	237			
1300	5.45	239			
1400	5.86	239			
1500	6.28	239			
Average		212			

is clearly an effect of the elastic interaction of fast neutron not thermalized by the moderator with the CR39. This effect is more evident for high energy neutrons because the moderation is less effective.

Table 2
Relative contributions to the signal due to low LET and high LET component.

Detector n°	Irradiation energy	High LET track density/cm^{-2}	Low LET track density/cm^{-2}	Ratio high LET to low LET
1792	19 MeV	1143	376	3.6
1808	0.565 MeV	1512	317	4.8
1762	Background	7	36	0.19

Table 3
Response of the Rem-Counter referred to the fluence (column 2) and to the ambient dose equivalent (column 3). The uncertainty associated to the response is around 10%.

Neutron energy/MeV	Track density per unit of fluence	Track density per μSv ($H^*(10)$)/μSv^{-1} cm^{-2}
0.535	1.17E-03	3.47
8	1.97E-03	4.81
14.8	1.69E-03	3.12
19	1.71E-03	3.39

3) In the V and area distributions the corresponding peaks are clearly visible.
4) Because the aim of the analysis is to count only tracks produced by alpha and ^{7}Li particles coming from the neutrons reaction on ^{10}B it is possible to define a threshold in terms of mean LET at about 120–130 keV/μm to reject the protons contribution and

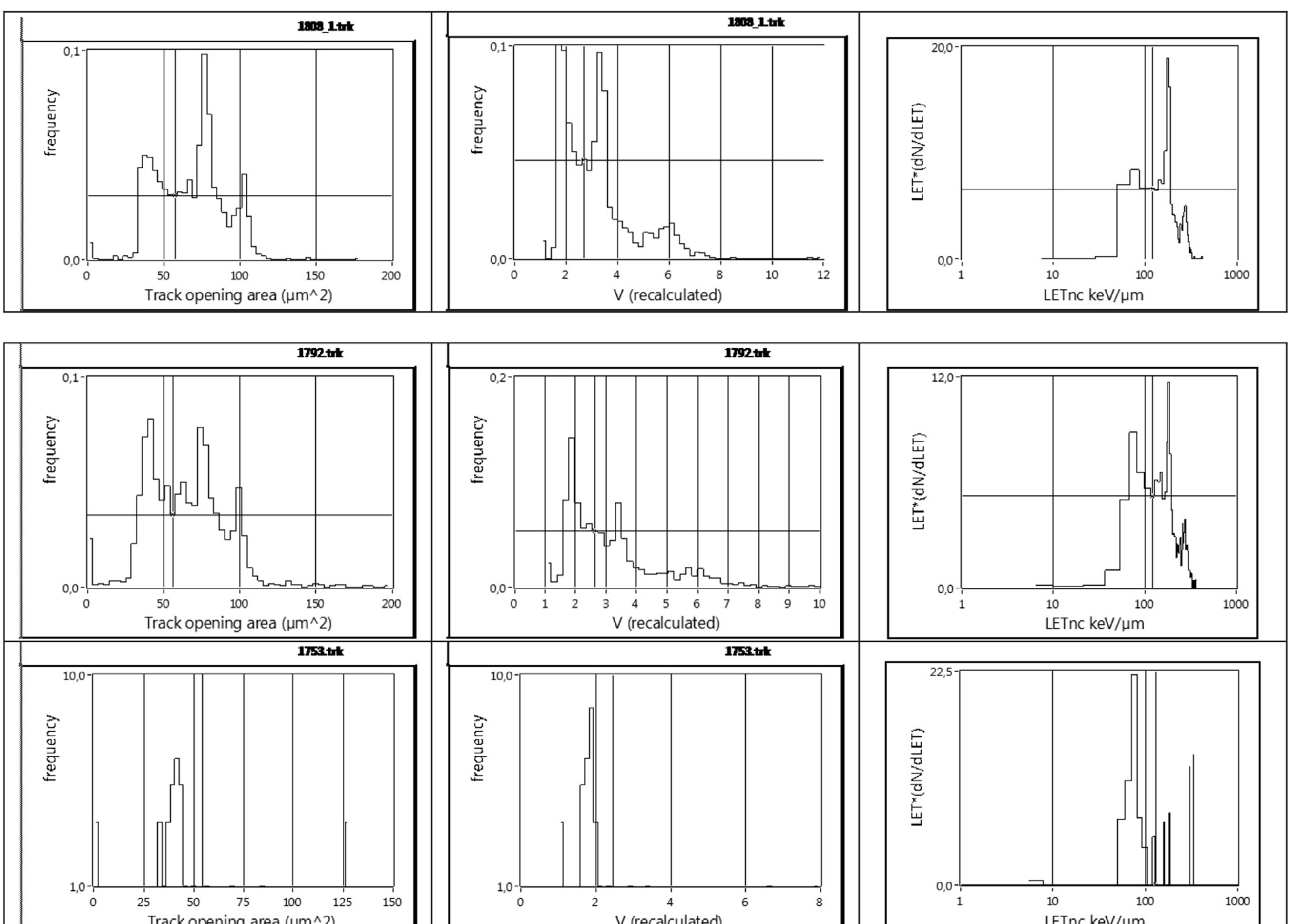

Fig. 2. Distributions of area, V and mean LET (LET_{nc} in the plot) assuming a removed layer of 6.7 μm. The upper graphs refer to the detector n°1808 irradiated with 0.565 MeV neutron energy. The middle graphs refer to the detector n° 1792 which is irradiated with 19 MeV neutron energy. The lower graphs refer to the background detector n° 1753.

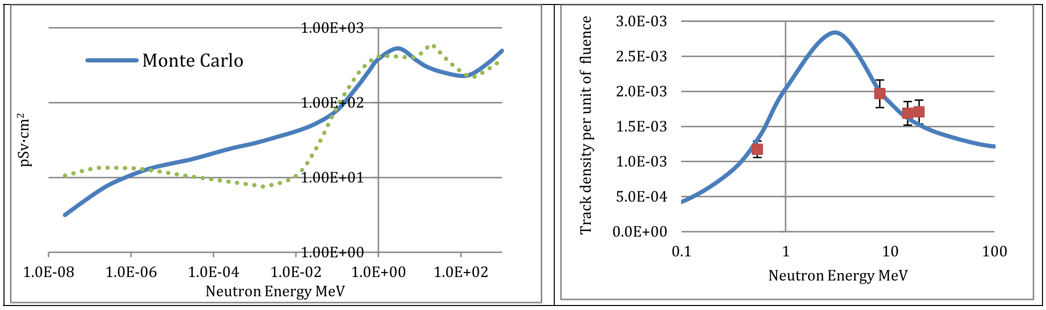

Fig. 3. Comparison between the simulated response function and the fluence to dose conversion coefficient (left). Comparison between the simulated response function and the experimental points (right). The response function has been rescaled to fit the fluence to dose conversion coefficients or the experimental response measured with the Am–Be neutron source, depending on the representation.

most of the noise due to surface defects that usually result in small tracks. The same threshold, expressed in terms of track area, is about 55 μm^2.

5) The background detectors have a typical track density in the high LET region that is 6.8 ± 2.6 cm^{-2}, so the background subtraction is important especially for low irradiated detectors. The LET distribution of detector n° 1753 shows that most of the background signal (mainly surface defects) is in the low LET region and it is effetely reduced by the LET threshold.
6) In Table 2 is reported a quantitative evaluation of the track density for irradiated and not irradiated detectors. The high LET to low LET ratio confirms in a quantitative way what discussed in the above point 2).

The passive Rem-Counter was irradiate at PTB to the monoenergetic neutron beams listed above and the result in terms of response versus neutron fluence and $H^*(10)$ is given in Table 3.

The Monte Carlo characterization of the Rem-Counter has been carried out using MCNPX 2.4.0 (LA06), simulating a source consisting of a 12.5 cm radius broad parallel beam of monoenergetic neutrons. The reaction rate on the ^{10}B has been scored by folding online the ^{10}B absorption cross section to the spectral fluence inside the converter, using the "tally multiplication" option of the software. 24 energies have been simulated, ranging from 25 meV up to 1 GeV. The response to a broad parallel beam with an Am–Be spectrum has been calculated too.

The conversion between the quantity scored by the simulation and the track density is affected by many factors (e.g. the etching conditions, the alpha and ^{7}Li self-absorption inside the ^{10}B converter etc …), and cannot be effectively determined based on theory or calculation. So an experimental conversion factor between the Monte Carlo tally and the track density has been determined by calibration with an Am–Be source, and is 4.45 ± 0.41 $\mu Sv^{-1}\ cm^{-2}$.

The response curve is shown in Fig. 3. In Fig. 3 (left) it has been rescaled to fit the fluence to dose conversion coefficients while in Fig. 3 (right) it has been rescaled to fit the experimental response measured with the Am–Be neutron source. The response to monoenergetic neutrons, in terms of track density per unit of fluence is plotted and a very good agreement between simulations and experimental results can be noted. The variation in response in terms of $\mu Sv^{-1}\ cm^{-2}$ shown in Table 3 reflects the overestimation and underestimation of the response function with respect to the fluence to $H^*(10)$ conversion coefficients curve.

4. Conclusions

The method of background reduction in the track analysis has proven to be very effective in separating the signal due to alpha particles and ^{7}Li nuclei from tracks induced by recoil protons and defects on the CR-39 surface. The simulated response function is in very good agreement with the experimental data. The not perfect agreement between the response function and $H^*(10)/\varphi$ conversion coefficients curve is quite typical of rem counters, that are usually designed to give a response with a precision acceptable for operational radiation safety over a very wide neutron energy range.

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